MERGER SITES OF DOUBLE NEUTRON STARS AND THEIR HOST GALAXIES

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ABSTRACT

Using the *StarTrack* population synthesis code we analyze the formation channels possibly available to double neutron star binaries and find that they can be richer than previously thought. We identify a group of short lived, tight binaries, which do not live long enough to escape their host galaxies, despite their large center-of-mass velocities. We present our most recent results on all possible evolutionary paths leading to the formation of double neutron stars, calculate their coalescence rates, and also revisit the question of the distribution of merger sites around host galaxies. For a wide variety of binary evolution models and galaxy potentials, we find that most of neutron star mergers take place within galaxies. Our results stem from allowing for radial and common envelope evolution of helium-rich stars (testable in the future with detailed stellar-structure and hydrodynamic calculations) and indicate that double neutron star binaries may not be excluded as Gamma-Ray Burst (GRB) progenitors solely on the basis of their spatial distribution around host galaxies. We also find, in contrast to Bethe & Brown (1998), that in a significant fraction of common envelope (CE) phases neutron stars do not accrete enough material to become black holes, and thus the channels involving CEs are still open for the formation of double neutron stars.

Subject headings: gamma rays: bursts — binaries: close — stars: evolution, formation, neutron

1. INTRODUCTION

Thirty years after the discovery of GRBs, their distance scale has been firmly established with the measurement of redshifts (Metzger et al. 1997). Cosmological GRB scenarios require an energy release of about 10^{51} ergs, pointing at violent events in the stellar evolution scenarios. Coalescences of double neutron star (NS-NS) binaries have been considered as possible GRB source (Paczynski 1986; Eichler et al. 1989). On theoretical grounds the timescale of such a merger is expected to be short (e.g., Ruffert & Janka 1999), of the order of a few milliseconds, however numerical simulations show that they might last up to 0.5 s (e.g. Lee & Kluzniak 1998). The discovery and observations of GRB afterglows and the identification of host galaxies have allowed comparisons of theoretical distributions of merger sites with the observed distribution of afterglow positions relative to GRB host galaxies. Such calculations (Bloom, Sigurdsson, & Pols 1999; Bulik, Belczynski, & Zbijewski 1999; Fryer, Woosley, & Hartmann 1999; Bloom, Kulkarni, & Djorgovski 2002) have found that NS-NS systems acquire rather high velocities and have long enough lifetimes that a large fraction of the coalescence events takes place outside the host galaxies. Black-hole neutron-star (BH-NS) mergers have also been found to take place outside host galaxies, yet with the tighter distribution of their merger sites.

In this paper we present a thorough investigation of the formation paths and merger sites of binaries containing two neutron stars using the *StarTrack* population synthesis code. In particular, we explore the implications of allowing for CE episodes involving helium stars.

2. MODEL DESCRIPTION

In our calculations we use the *StarTrack* population synthesis code described in detail in Belczynski , Kalogera & Bulik (2002a). Dynamical evolution of binaries, in particular effects of kicks and mass loss due to supernovae (SN) explosions, in diffrent galactic potentials is presented in Belczynski, Bulik & Rudak (2002b).

In order to investigate the systematic inaccuracies of binary population synthesis methods, we vary many of the parameters describing the stellar evolution. We define standard model with: Cordes & Chernoff (1998) kick velocity distribution; maximum NS mass $M_{\rm max,NS} = 3.0\,{\rm M}_\odot$; $\alpha_{\rm CE} \times \lambda = 1$, where $\alpha_{\rm CE}$ – CE efficiency (Webbink 1984), λ – numerical factor describing stellar density distribution (de Kool 1990); $\rm f_a = 0.5$, $j_{\rm a} = 1.0$, in non-conservative stable MT, $\rm f_a$ denotes the part of the mass lost by donor and accreted by the companion and the rest is lost from a system with angular momentum equal to $2\pi j_{\rm a} A^2/P$, where A and P are the orbital separation and period, respectively; $M_{\rm conv} = 4.5\,M_\odot$, evolved helium stars of mass below $M_{\rm conv}$ are assumed to develop deep convective envelopes; continuous star formation rate (SFR); initial mass function (IMF) $\propto M_1^{-2.7}$; $f_{\rm bi} = 50\%$, binary fraction; $\Phi(q) = 1$, initial mass ratio distribution, $q \equiv M_2/M_1$, where M_1 is mass of primary, and M_2 is mass of secondary; partial fall back (FB) allowed for stars with $5.0 < M_{\rm CO} < 7.6\,M_\odot$, where $M_{\rm CO}$ is final stellar CO core mass; in CEs hyper-critical accretion (HCA) onto NS/BH allowed. All the other models, presented in Table 1, differ only by the value of one parameter from the standard model (A) and are described in detail in Belczynski et al. (2002b).

3. RESULTS

Our results depend crucially on the treatment of immediate progenitors of neutron stars (NS): low-mass helium stars, and in particular their radial expansion as well as their behavior during mass transfer (MT) episodes in close binaries. Although the radial expansion has been acknowledged in the literature, it has not been widely used in population synthesis studies. In our earlier work (Belczynski & Kalogera 2001) we argued that the two evolved low-mass helium stars (and thus with at least partially convective envelopes) may drive dynamically unstable MT, leading to CE evolution. In the present study we allow low-mass helium stars to expand during their evolution, and possibly initiate MT in close binaries. If an evolved low-mass helium star is more massive than its companion, we assume that the MT will be dynamically unstable and will lead to CE phase. We treat such CE phases with the standard "alpha" prescription (Webbink 1984), to check whether systems survive the episode or result in mergers. The standard description of CE phase has been used successfully for H-rich giants, however without detailed hydrodynamical simulations, we cannot address the question whether it also works in the case of low-mass He-rich giants. Since hydrodynamical simulations are beyond the scope of this study, we also present calculations in which we assume that all MT episodes of low-mass helium stars lead to mergers, and in which the helium stars are not allowed to expand radially.

3.1. Formation Channels

We find that coalescing NS-NS binaries are formed in various ways, including more than 14 different evolutionary channels (Belczynski et al. 2002a). However, the entire population may be divided into three groups. *Group I* consists of non-recycled NS-NS systems identified by Belczynski & Kalogera (2001). Progenitors of these systems end their evolution in a double CE of two evolved helium stars. If a merger is avoided and the CE is ejected, a tight binary consisting of two bare carbon-oxygen (CO) cores is formed. The CO cores form neutron stars in two consecutive Type Ic SN explosions. Provided, that the system is not disrupted by SN kicks and mass loss, two neutron stars form an eccentric and tight binary with the unique characteristic that none of the neutron stars had a chance to be recycled. Progenitors of *Group II* NS-NS binaries end their evolution in a CE episode involving an evolved low-mass helium star donor and a neutron star companion. Despite of the short timescale of the CE phase, the NS may increase its mass due to hyper-critical accretion (e.g., Brown 1995; Bethe & Brown 1998). If system avoids merger in the CE phase and if NS does not collapse into a black hole (BH), a system consisting of recycled pulsar and bare CO core is formed. After a Type Ic SN explosion, a very tight and eccentric NS-NS binary is formed. These systems (see also Belczynski et al. 2002a) are characterized by very short lifetimes. Systems of *Group III*, consisting of all other NS-NS, are formed along more or less classical channels (Bhattacharya & van den Heuvel 1991).

In Figure 1 we show an example of the formation of a tight NS-NS binary of Group II. The evolution begins with two massive stars in a rather wide and eccentric orbit (stage I). The primary evolves off the main sequence, expands to giant dimensions circularizing the initially eccentric orbit. Once the primary reaches its Roche lobe, nonconservative but dynamically stable MT begins (stage II). The donor envelope is in part accreted onto the main sequence (MS) companion and in part lost from the binary. The post-MT binary (stage III) consists of the exposed helium core of the primary and the MS secondary, which increased its mass and was rejuvenated. The low-mass helium star evolves through core and shell helium burning, and radially expands significantly, although it never fills its Roche lobe. Its evolution ends with a Type Ib SN explosion forming the first NS in the system. Due to the asymmetric SN explosion and the associated mass loss, the post-SN system is eccentric and the orbit widens (stage IV). Next the secondary ends core hydrogen burning and evolves toward the giant branch. The associated radial expansion leads to Roche lobe overflow, and the orbit is again tidally circularized. Since in this case the donor is much more massive than its NS companion, the issuing MT is dynamically unstable, and a CE event ensues. Once the NS is engulfed in the expanding envelope of the original secondary, it experiences hyper-critical accretion (e.g., Bethe & Brown 1998). The spiral in of the NS toward the helium core of the secondary ends, when the CE is expelled from the binary, at the expense of orbital energy. The orbital separation is greatly reduced, and a close binary with a NS and a low-mass helium star is formed (stage VI). The helium star evolves through subsequent burning of elements and eventually acquires a "giant-like" structure, with a developed CO core and a partially convective envelope. When it fills its Roche lobe another CE phase begins (stage VII). However, this time, the envelope is of much lower mass, and the binary orbit is not as greatly reduced and the first NS does not accrete as much mass. At the end of this phase the CO core of helium star is exposed (stage VIII), and it eventually explodes as a Type Ic SN. Due to the very tight pre-SN binary orbit, the probability of survival through the SN is very high, and a very tight and highly eccentric NS-NS binary is formed with a merger time of $\simeq 0.7$ Myr.

Group II strongly dominates the population of coalescing NS-NS systems (87.4%, for the standard model calculation) over group III (4.2%) and I (8.4%). The formation of Group I and II systems depends crucially on the radial evolution (expansion) of low-mass helium stars and their response to mass loss. In model N we do not allow for any helium-star expansion, and in model H2 we assume that all Roche-lobe overflow events from helium-stars lead to mergers (independent of their mass). In these models we find that NS-NS systems are formed via classical channels (group III). The merger times of the group III systems are typically of the order of a Gyr. The systems in group I and II systems are initially much tighter and thus short lived: their merger times are typically of the order of a Myr or even shorter (see Belczynski et al. 2002a).

3.2. Coalescence rates

In Table 1 we present the coalescence rates of NS-NS binaries for all the models we investigate. The rates have been calibrated for the Galactic Type II SN rates obtained by Capellaro, Evans & Turatto (1999). Our standard model rate corresponds to about 50 coalescence events of NS-NS per Galaxy per Myr. However, due to the model uncertainties, this rate varies in a wide range of 1-300 events per Galaxy per Myr, depending which parameter values we choose to adopt.

As shown in earlier studies (e.g., Lipunov, Postnov & Prokhorov 1997; Belczynski & Bulik 1999), the coalescence rates depend strongly on the assumed kick velocity distribution (see models B1-13). Since we assume a rather high value for the maximum NS mass ($M_{\rm max,NS} = 3.0 M_\odot$) for the standard model, we also calculate rates for models (D1 and D2) with lower $M_{\rm max,NS}$. The least affected subgroup is that of the non-recycled NS-NS binaries, as they consist of low-mass NS. However, the rates for group II and III are reduced significantly. This is due to the specific formation channels of these two groups, in which many compact objects are formed with masses over 1.5 and 2.0 $M_\odot$. In models H2 and N, NS-NS are formed only in group III. In model H2, with the lowest predicted coalescence rate of NS-NS systems, none of helium stars are allowed to develop convective envelopes, therefore we assume that any MT phase initiated by a helium star lead to a binary component merger. In model N, helium stars are not allowed to expand, and therefore they never interact, which suppresses formation of NS-NS systems in the new channels.

All models (except C) include hyper-critical accretion onto compact objects in CE episodes. We find, in contrast to Bethe & Brown (1998), that in most cases NS do not accrete enough material to become BH, and thus the channels with phases of CE are still open for the formation of coalescing NS-NS binaries. This discrepancy is due to two facts. First, their assumption of $M_{\rm max,NS} = 1.5 M_\odot$, which we find very low in view of the high

NS mass estimates in Cyg X-2: $1.78 \pm 0.23 M_\odot$ (Orosz & Kuulkers 1999) and in Vela X-1: $1.9^{+0.7}_{-0.5} M_\odot$ (van Kerkwijk et al. 1995). Second, their approximate[1] treatment of accretion onto NS results in higher final compact object masses than in our exact numerical solution. Both, our detailed treatment of the hyper-critical accretion and the variation of coalescence rates of compact object binaries for all our models is given in Belczynski et al. (2002a).

3.3. Distribution of merger sites

We first consider the distributions of merger sites for each Group identified above. In the left panel of Figure 2 we present the case of a massive Milky Way like galaxy. The distribution of merger sites of groups I and II follows closely the initial stellar distribution in this galaxy. This is expected since these systems are very tight, and therefore their lifetimes as NS-NS systems are typically a few Myr. Even with a velocity of a $1000 \mathrm{km\,s^{-1}}$ a NS-NS system will move only out to ~ 1 kpc before it merges. This is also seen in the right panel of Figure 2 where we show the distributions around a small mass host. The binaries of group I and II merge within such galaxies, and the distribution of the merger sites follows closely the initial distribution of stars. The classical systems, (Group III) have much longer merger times and therefore some of them manage to escape even from high mass hosts, see Figure 2. In the case of small galaxy the distribution of merger sites of group III binaries contains a large fraction that merges far outside the host. One must bear in mind that our simulations show that the entire population of NS-NS systems is dominated by group II systems, and group III systems are the smallest subgroup.

We present the distributions of NS-NS merger sites around the two model galaxies for all our evolutionary models listed in Table 1 in Figure 3. In the case of a massive host galaxy, all distributions except for models H2 and N nearly overlap. The escaping fraction, defined as numbers of systems merging further than 20 kpc from the host is always smaller than five percent. In models H2 and N formation of group I and group II systems is suppressed and the escaping fraction is much larger. In the case of a dwarf host (right panel of Figure 3) the escaping fraction varies between 5 and 15%. For models E3 ad F2 the distributions clearly stand out, yet even in these cases nearly 80% of the mergers take place within the host galaxies. The E3 systems are formed assuming a very high CE efficiency, and therefore are still wide after the CE phase. Thus they are relatively long lived and this broadens the

[1]Bethe & Brown (1998) have assumed that the NS mass during CE is much smaller than the companion mass and they have neglected it in their eq. 5.5. However, we find this is not always true, e.g., see stage (VII) in our Fig. 1: with accreting NS of $1.8 M_\odot$ and helium giant donor of only $3.1 M_\odot$.

distribution of merger sites. In model F2 every MT event (except a CE phase) is treated conservatively, i.e., all material lost from the donor is accreted by the companion. Therefore the separation following MT events is wider, as no material and thus no angular momentum is lost from the binary. Wider systems live longer and therefore may merge further from the host. Models H2 and N, roughly represent distributions of NS-NS binaries formed only through classical channels with long merger times, that merge far from their birth places (for small hosts the escaping fraction is $\sim 70\%$).

4. Conclusions

Previous calculations of distribution of merger sites of NS-NS binaries showed that NS-NS binaries merge predominantly outside of host galaxies. This result was used as an argument against the NS-NS systems as GRB progenitors. With the calculations presented here we show that the NS-NS population may consist primarily of systems with small orbital separations and consequently short merger times, which merge close to the place where they had been formed. Such systems are formed along the newly identified formation channels, opened in our calculations for the two following reasons. The first is our treatment of the evolution of low-mass helium stars, which are allowed to form partially or fully convective envelopes. The second is that we have considered double common envelope episodes of two giant stars (H- and He-rich) leading to ejection of their combined envelopes. These are the two major features of our calculations that allow the formation of the two new subpopulations of NS-NS binaries. Evolution of helium stars in CE phases has been considered qualitatively in earlier studies (van den Heuvel 1992; Taam 1996). MT interactions involving helium stars (although not CE phases) have been included in population synthesis study of Tutukov & Yungelson (1993).

If NS-NS mergers are the progenitors of short bursts then we find that they should lie within galaxies just as the long bursts do. We note that the BH-NS mergers take place preferentially outside galaxies (for details see Belczynski et al. 2002b). Current and future space missions will hopefully measure precise positions of short bursts and settle the issue of their progenitors.

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Table 1. Galactic NS-NS Coalescence Rates (Myr^{-1})

Model	I	II	III	Total	Model details[a]
A	4.4	46.1	2.2	52.7	standard model
B1	6.0	286.4	0.0	292.4	zero kicks
B3	6.4	295.7	0.1	302.2	$\sigma = 20\,\mathrm{km\,s^{-1}}$
B6	6.5	219.8	0.6	226.8	$\sigma = 50\,\mathrm{km\,s^{-1}}$
B7	5.2	121.0	1.9	128.1	$\sigma = 100\,\mathrm{km\,s^{-1}}$
B9	4.3	27.5	1.4	33.2	$\sigma = 300\,\mathrm{km\,s^{-1}}$
B12	1.9	5.8	0.3	8.0	$\sigma = 600\,\mathrm{km\,s^{-1}}$
B13	4.6	84.1	2.3	91.0	"Paczynski" kicks
C	3.2	37.5	2.6	43.2	no HCA in CEs
D1	4.9	28.0	0.7	33.6	$M_{\mathrm{max,NS}} = 2\,\mathrm{M}_\odot$
D2	3.6	5.5	0.0	9.1	$M_{\mathrm{max,NS}} = 1.5\,\mathrm{M}_\odot$
E1	0.4	2.0	0.3	2.7	$\alpha_{\mathrm{CE}} \times \lambda = 0.1$
E2	3.1	19.0	1.4	23.5	$\alpha_{\mathrm{CE}} \times \lambda = 0.5$
E3	5.2	99.8	4.0	109.0	$\alpha_{\mathrm{CE}} \times \lambda = 2$
F1	2.3	18.6	1.2	22.1	$\mathrm{f_a} = 0.1$
F2	2.3	44.6	7.5	54.3	$\mathrm{f_a} = 1$
G1	3.3	38.7	1.9	43.9	wind decreased by 2
G2	7.3	82.7	2.2	92.2	wind increased by 2
H1	3.3	33.0	1.6	37.9	$M_{\mathrm{conv}} = 4.0\,M_\odot$
H2	0.0	0.0	0.9	0.9	$M_{\mathrm{conv}} = 0\,M_\odot$
I	4.0	47.4	3.2	54.5	burst-like SFR
J	4.4	50.7	3.0	58.1	(IMF):$\propto M_1^{-2.35}$
K1	1.8	19.7	1.0	22.5	binary fraction: 25%
K2	7.4	79.0	3.8	90.2	binary fraction: 75%
L1	6.3	66.1	6.5	78.9	$j_{\mathrm{a}} = 0.5$
L2	2.0	9.6	0.4	12.0	$j_{\mathrm{a}} = 2.0$
M1	0.2	5.8	0.2	6.2	$\Phi(q) \propto q^{-2.7}$
M2	14.0	94.3	5.9	114.2	$\Phi(q) \propto q^{3}$
N	0.0	0.0	34.4	34.4	no He-star expan.
O	4.3	45.0	2.6	51.9	extended FB

[a]For definition of parameters see § 2

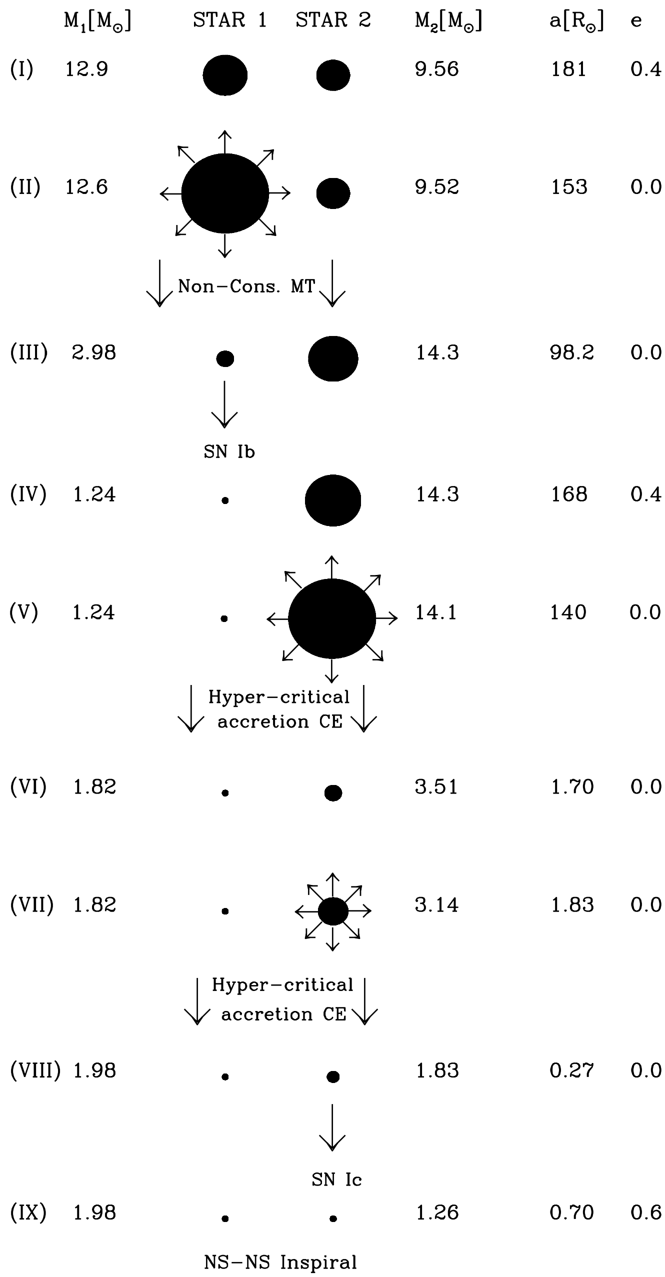

Fig. 1.— Stages of the dominating NS-NS formation path; after 23 Myr of evolution and two SN, a tight NS-NS binary with a merger time of about 0.7 Myr is formed (details are given in § 3.1).

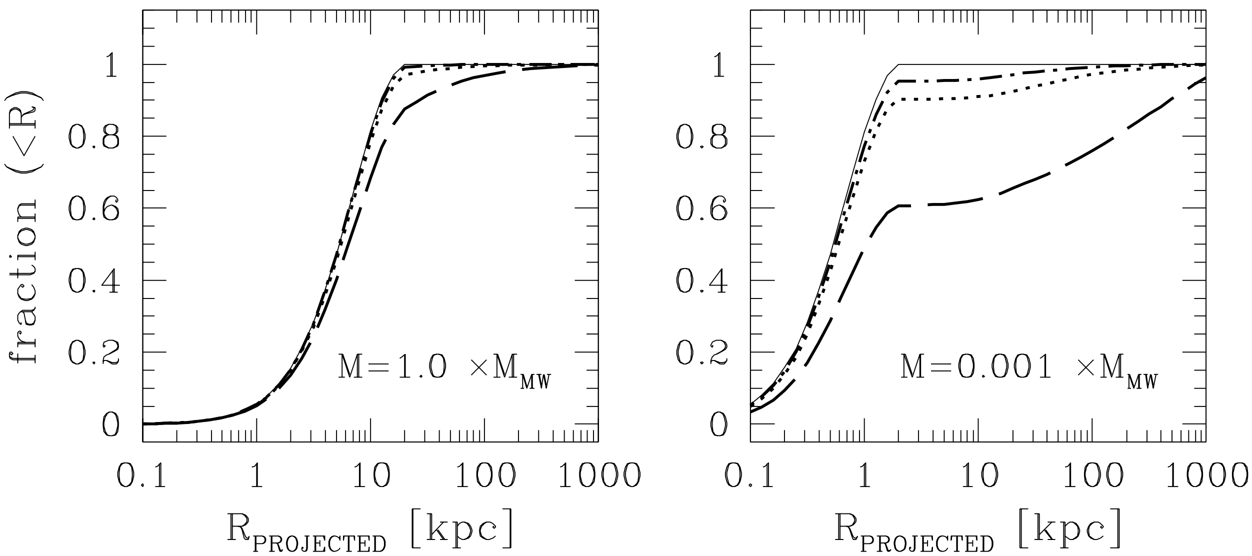

Fig. 2.— Standard Model. Cumulative distributions of merger sites of coalescing NS-NS binaries, around a massive galaxy with $M = M_{\rm MW}$ (left panel) and dwarf galaxy with $M = 0.001 \times M_{\rm MW}$ (right panel); group I: thick dotted line, group II: thick dot-dashed line, and group III: thick long dashed line. and the initial distribution of primordial binary population within the given mass galaxy is given with the solid thin line.

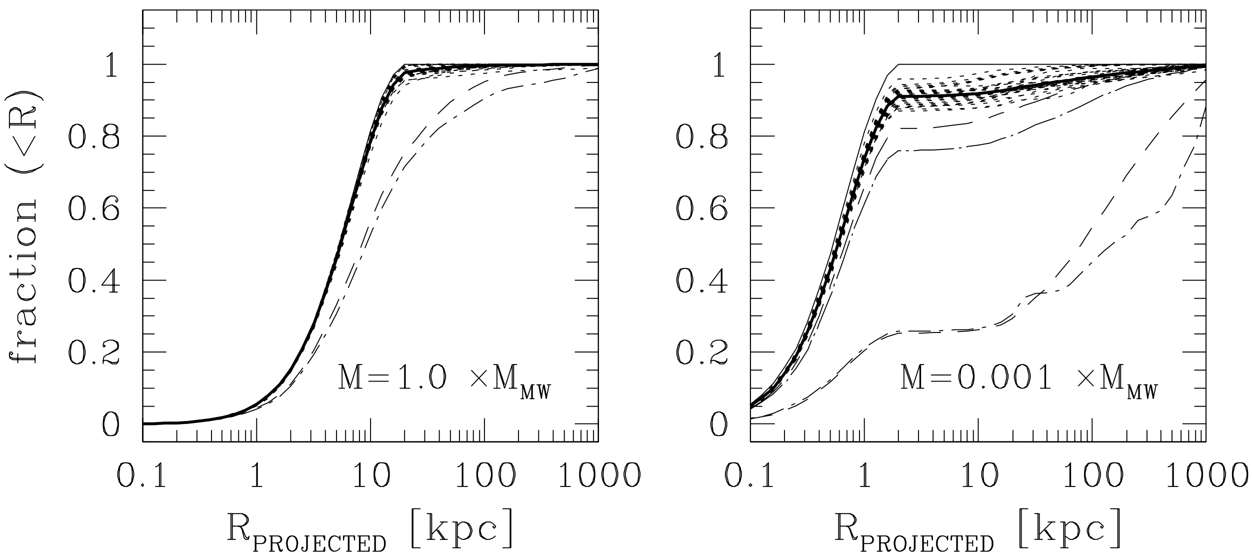

Fig. 3.— Parameter Study. Cumulative distributions of NS-NS merger sites for different evolutionary models. The left panel shows distribution for NS-NS systems born in a massive galaxy ($M = 1.0 \times M_{\rm MW}$) and the right panel for a dwarf galaxy ($M = 0.001 \times M_{\rm MW}$). Initial distribution of primordial binary population within the given mass galaxy is plotted with the thin solid line, while different model distributions are plotted with dashed and dotted lines. Three most extreme distributions are marked: with short-long dashed line that of model E3, with dotted long dashed line that of model F2, dotted short dashed line that of model H2 and with short dashed line that of (nonphysical) model N. Standard model distribution is marked with thick solid line.